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Radio Observations of Nearby HST BL Lacs

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Abstract. We present a radio/optical study of a sample of BL Lac objects at arcsecond and milliarcsecond resolution. The sample consists of 30 nearby ($z < 0.2$) BL Lacs, mostly X-ray selected. These nearby objects are weak in the radio, yet we have successfully observed them with the VLA, VLBA and EVN, revealing interesting morphologies. Most importantly, we find evidence of relativistic boosting even in these low power sources (dominant core, one-sided jets). We present a radio/optical comparison including HST observations which have detected compact optical cores in all objects.

1. Introduction

In spite of much success and major achievements, the unification of FR I radio galaxies and BL Lac type objects is still an open issue, requiring further studies. In particular, a study of a sample of nearby BL Lacs can be informative. In fact, considering the closest objects allows us to study also the faintest sources, which is important in many respects.

First, the weak end of the luminosity function has been poorly studied in the radio at high resolution. The only extensive study on a complete sample of BL Lacs is based on objects of any redshift, brighter than 1 Jy at 1.4 GHz (Stickel et al. 1991). This excludes the weakest objects in the radio, i.e. those objects for which the low luminosity peak in the SED rises more slowly, peaking at X-ray (High frequency peaked BL Lacs, HBL) rather then optical/UV (Low frequency peaked BL Lacs, LBL). This objects are less well known and somehow more extreme; for example, they are the best candidates for the presence of TeV emission. Last but not least, in accordance with the subject of this conference, the milliarcsecond resolution obtainable with VLBI makes it possible to investigate an extraordinarily fine linear resolution (1 mas $\sim$ 2 pc at

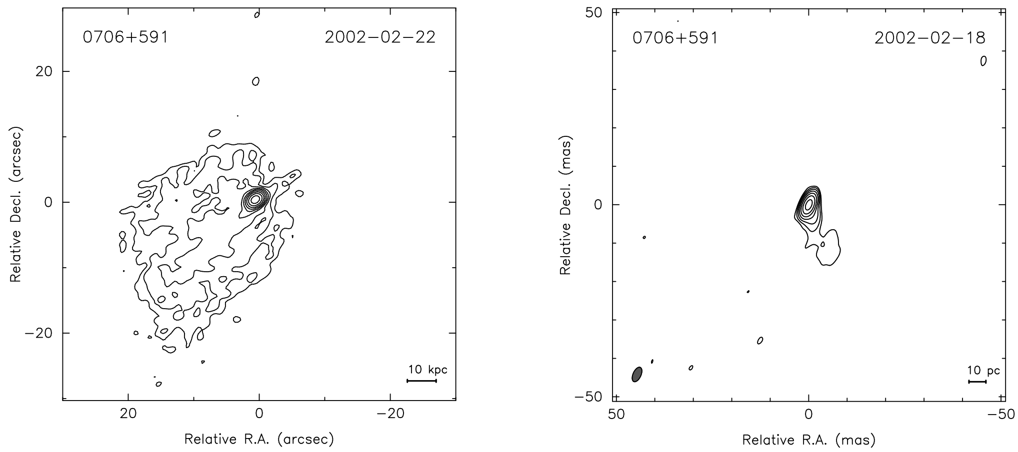

Figure 1. Images of 0706+591. Left: VLA at 1.4 GHz, A configuration (HPBW 1.6" × 1.2", PA −57°); right: VLBA at 5 GHz. (HPBW 3.6 × 1.4 mas, PA −23°)

$z = 0.1$, $H_0 = 65\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$) providing a wealth of information at centimeter wavelengths.

For these reasons, we are considering a sample of 30 objects, selected from a large set of 110 BL Lac objects with the condition of $z < 0.2$. High resolution observations in the optical are presented in Falomo et al. (2000). The average total radio power at 1.4 GHz, as derived from the NVSS (Condon et al. 1998), is almost two orders of magnitude lower than in the 1 Jy sample ($\langle \mathrm{Log}P_{1.4\mathrm{GHz}} \rangle = 24.8 \pm 0.6$ and $\langle \mathrm{Log}P_{1.4\mathrm{GHz,1Jy}} \rangle = 26.8 \pm 0.9$, respectively). Some well known objects, such as BL Lac itself, Mkn 421, 3C 371 are common to both samples; however, about 50% of the objects in our sample have never been observed with any VLBI array, or even with the VLA. We present here results for three objects in the sample (Sect. 2), and discuss in the light of our new observations some of the properties of the sample as a whole (Sect. 3).

2. Observations and Images

We have obtained observing time with the VLA at 1.4 GHz, in A (10 hrs/19 sources) and C (5 hrs/9 sources) configuration, in order to complete observations on kiloparsec scales for all the sources. The observations were completed between February and October 2002.

At pc scale resolution, 15 out of the 30 sources in the sample needed new or higher fidelity maps. We observed all these sources with the VLBA at 6 cm on 2002 Feb 17, 18, and 19, for about one hour each. More observations were obtained with the EVN at 18 cm (12 hrs/6 sources on 2002 Jun 7) and the EVN+MERLIN at 6 cm (12 hrs/2 sources on 2002 May 27).

0706+591 – This object is located at $z = 0.125$ and is classified as HBL. The VLA image in A configuration (left panel in Fig. 1), reveals a dominant core and an extended structure oriented at PA $\sim 130°$ (measured north to east). The total flux density is 161 mJy. The VLBA image at 5 GHz (right panel) has

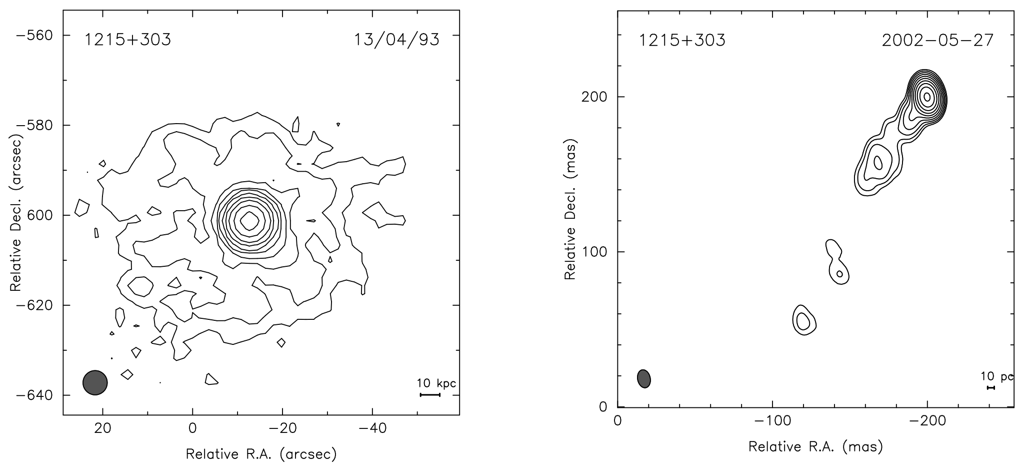

Figure 2. Images of 1215+303. Left: image from the FIRST survey (Becker et al. 1995); right: EVN+MERLIN at 5 GHz.

a peak of 33 mJy/beam and presents a jet in a direction perpendicular to the kpc scale. This is quite common behaviour for BL Lac objects in our sample.

1215+303 – The HBL 1215+303 is located at $z = 0.130$. For this object, a good map is available in the FIRST survey (Becker et al. 1995), as shown in Fig. 2 (left). A 377 mJy core dominates a symmetric halo structure of about 50" diameter. No preferred direction is visible on this scale. For this reason, we performed EVN+MERLIN observations at 5 GHz, in order to image the inner structure out to the largest possible distance from the inner core. The right panel in Fig. 2 shows a one-sided, long, straight jet. The large jet/counter-jet ratio ($R \gtrsim 150$) indicates that the effects of the beaming are important in this source; indeed, one could expect a small angle to the line of sight, if the kpc halo structure were interpreted as a lobe seen end-on.

2344+514 – This is one of the closest objects in the sample ($z = 0.044$) and presents a puzzling morphology (Fig. 3). It looks like a double when observed in C configuration, with faint, extended emission connecting the two compact components. A third, misaligned, less bright component could be a background

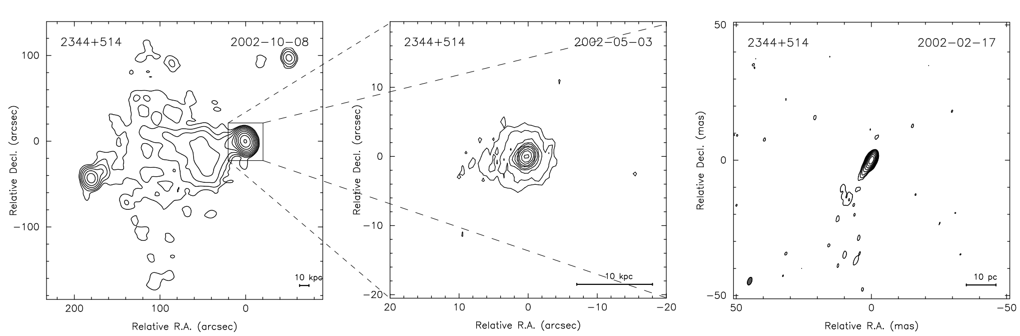

Figure 3. Images of 2344+514. From left to right: VLA at 1.4 GHz, C configuration; VLA at 1.4 GHz, A configuration; VLBA at 5 GHz.

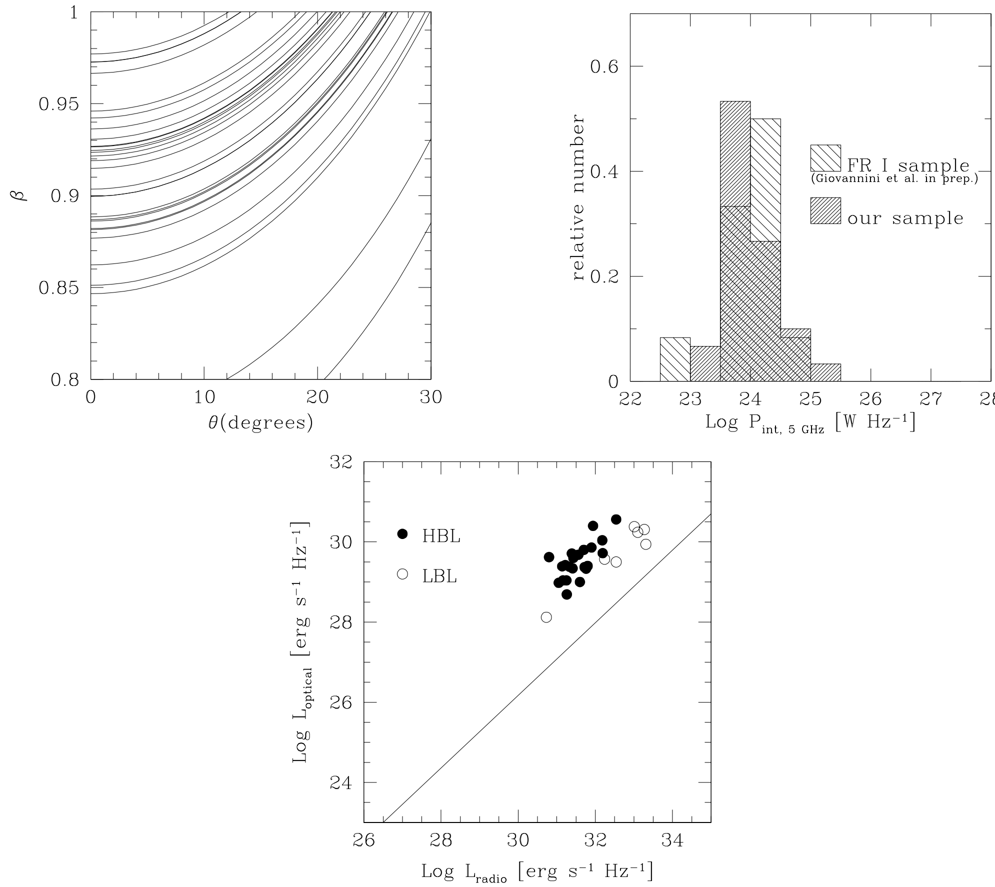

Figure 4. Top left panel: the (θ, β) plane; each curve corresponds to one object. Top right: histogram of de-boosted core powers for the present sample and FR Is of similar z. Bottom: Optical vs. radio core luminosities; the straight line represents the linear correlation found by Chiaberge et al. (2000) for radio galaxies.

object (even if it seems aligned with a small extension in the faintest component of the double). However, imaging of the strongest component in A configuration reveals a core-halo morphology. Finally, the high resolution VLBA image shows a ~ 20 mas jet almost orthogonal to the large scale structure axis. Note that *Chandra* observations have revealed diffuse X-ray emission in the environment of this source (Donato et al. 2003).

3. Discussion

Our radio data show a variety of behaviours: core-jet, core-halo, double compacts and even a few head-tails, clearly related to the membership to galaxy clusters. However, all the sources are characterized by a compact, bright, dominant radio core in the BL Lac position. Thanks to the well-known correlation

between the core and total radio power (Giovannini et al. 1988; 2001), we are therefore able to derive the allowed range of β and θ for all the sources in the sample (see Fig. 4, left panel). We obtain values in good agreement with the expectations of the unified scheme; in particular $\beta \gtrsim 0.9$ (i.e. relativistic velocity) and $\theta \lesssim 25°$ (small angle of view).

It is not possible to decide which combination of these parameters is the most realistic and we do not even know if all the objects have the same intrinsic properties. However, following Giovannini et al. 2001, we assume a Lorentz factor $\Gamma = 5$ ($\beta = 0.98$) and derive for every single source the corresponding angle θ_5 and Doppler factor δ_5. Then, we use these results to de-boost the core power at 5 GHz and obtain intrinsic values. The comparison with a sample of FR I radio galaxies of similar redshift (Giovannini et al., in prep.), shows that the two population overlay well (Fig. 4, right panel).

Finally, we compare the luminosities of the BL Lac cores in the radio and in the optical. Figure 4 (at bottom) shows that the luminosities correlate with a linear law, just as the 3C and B2 radio galaxies do (straight line). This indicates a common origin for both radio and optical emission. There is however a considerable offset ($\sim$ 2 orders of magnitude) between BL Lacs and radio galaxies, suggestive of a larger beaming factor for the region emitting at optical frequency (Chiaberge et al. 2000). In turn, this can be explained by the presence of a two-velocity regime (fast inner spine and slow external shear) in pc scale jets and/or by a spine velocity decrease from the optical to the radio emitting region.

4. Summary

We have completed parsec and kiloparsec scale radio observations for all sources in our sample. All objects show a dominant, compact core surrounded by different features: jets, halos, other compact components; bending in jets from pc to kpc scale is often present. We derive luminosities consistent with a parent population of FR I type and confirm the existence of a linear correlation between optical and radio core luminosity.

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